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ANALYSIS OF STRESS-STRAIN BEHAVIOR OF TUNGSTEN FIBER REINFORCED COPPER COMPOSITES

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ABSTRACT

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An investigation was conducted to determine the stress-strain behavior and tensile properties of metallic composites and to relate them to the properties of the base materials. Room temperature tensile and dynamic modulus tests were used to determine these properties. The composites were reinforced with either continuous or discontinuous tungsten fibers. The tensile properties and stress-strain behavior of composites reinforced with either type of reinforcement were similar and in both cases, the full strength of the fiber was utilized.

AUTHOR

INTRODUCTION

To meet the demand for improved structural materials, considerable effort is being directed toward the creation of composite materials. One such material under investigation is the fiber-reinforced composite, in which a ductile, relatively weak matrix is reinforced with high-strength fibers.

Some work has been done on the reinforcement of metallic matrices with metallic fibers (refs. 1 to 5) as well as with ceramic whisker reinforcement (ref. 6). Summaries of much of this work have been published by Machlin (ref. 7) and Baskey (ref. 8). Work done at the Lewis Research Center of NASA (refs. 9 to 12) has involved the making and testing of composites composed of a fiber, tungsten, and a matrix, copper, which were insoluble in each other. An equation was presented that showed the relation between the ultimate tensile strength of the composites and the strengths and relative volume percents of the components. This relation was verified experimentally for composites containing fibers extending the full length of the specimen as well as for composites reinforced with short length or discontinuous fibers. Since the publication of the preliminary results (refs. 9 to 11), additional data have been obtained. This paper presents these data as well as analyses of the stress-strain behavior and the mechanics of deformation of uniaxially oriented, fiber-reinforced metallic composites, in which both components are mutually insoluble.

EXPERIMENTAL PROCEDURE

Composites were made with high-purity copper as the matrix and 3-, 5- and 7-mil-diameter tungsten wire as the reinforcing fiber. Some specimens were made in which the reinforcing fiber extended completely through the full length of the composite test section. Composites were also made with short length (3/8 inch long) 5-mil-diameter tungsten fibers as discontinuous reinforcement. The specimens were prepared by infiltrating copper into packed bundles of tungsten wire at 2200° F. Room-temperature tensile tests were conducted on the composites, stress-strain curves were obtained, and ultimate tensile strength and elongation were measured. Dynamic modulus of eleasticity, based upon the resonant frequency induced in the flexural mode of vibration, was also determined for the composites and the components. A more detailed discussion of the experimental procedure employed in this investigation may be found in ref. 12.

RESULTS

Room-temperature tensile tests were conducted on 3-, 5-, and 7-mil-diameter tungsten wires which had been annealed for 1 hr. at 2200° F and show the tensile strength of the wires to be 331,000, 327,000, and 290,000 psi, respectively. Since all the composites were infiltrated under these conditions, the strengths were considered to represent the strength of the fibers in the composites throughout this study.

The average tensile strength of the annealed copper used as the matrix in this investigation was 27,800 psi.

Results of room-temperature tensile tests on composites reinforced with 3-, 5-, or 7-mil-diameter tungsten fibers are plotted as functions of composition in Fig. 1. These data represent previously reported data (refs. 9 to 11) as well as data more recently obtained. The line shown on each curve represents a prediction of tensile strength as a function of composition; the calculation of this line was explained in references 9 to 11.

A similar plot is presented in Fig. 1(d) for composites reinforced with short length, discontinuous 5-mil-diameter tungsten fibers. Again, both the previously reported and the recent data are presented, and the line shown is identical to that shown for 5-mil-diameter continuous-fiber-reinforced composites shown previously.

A plot of percent elongation at failure of composites reinforced with 5-mil-diameter continuous fibers as a function of volume percent fiber is shown in Fig. 2. Also shown are the elongation of the tungsten wire annealed under the conditions of infiltration, and the fully annealed copper. Elongation was measured from the crosshead movement of the Instron tensile machine in which the material was tested. The elongation at fracture decreases with increasing fiber content within the range between the elongation of pure copper and that of the tungsten wire. While the fibers alone show elongation at failure ranging from 1.3 to 2.9 percent, the composites show a much greater elongation.

Stress-strain curves for copper, tungsten wire, and composites reinforced with 3-, 5-, or 7-mil-diameter tungsten wire are shown in Fig. 3. The curves shown for the tungsten wire were taken from the crosshead motion of the tensile machine, while those for the composites and copper were determined by using an extensometer. These curves show that both the composites and the tungsten wire reach their ultimate tensile strength at about 1.4 percent strain. Furthermore, the curves show that the copper passes into plastic flow at a very low strain, while the tungsten is elastic to about 0.4 percent strain.

An enlargement of the low strain region of the curve is shown in Fig. 4. The copper is strained elastically only to about 0.03 percent strain. Beyond this, it is strained plastically, and the copper as well as the composites show a change in the slope of their stress-strain curves. The slope of the stress-strain curve prior to the change in slope (~0.03 %) may be termed the initial modulus of elasticity, while the slope afterward may be called the secondary "modulus of elasticity."

The secondary moduli for various copper-tungsten composites are plotted in Fig. 5. A least squares fit of the data shows an intercept of 56×10^6 psi at 100 percent tungsten and about 0.9×10^6 psi at 100 percent copper.

Results of yield-strength determinations for composites reinforced with various amounts of continuous 5-mil-diameter tungsten fibers and plotted as a function of fiber content are depicted in Fig. 6. These results were obtained by using the 0.2-percent offset method.

Results of dynamic modulus of elasticity measurements made at room temperature on specimens reinforced with continuous or discontinuous fibers are shown in Fig. 7.

DISCUSSION

Prior to a description of the behavior of the composites, the following postulated stages of deformation should be considered:

Stage I - Elastic deformation of fiber; elastic deformation of matrix.

Stage II - Elastic deformation of fiber; plastic deformation of matrix.

Stage III - Plastic deformation of fiber; plastic deformation of matrix.

Stage IV - Failure of fiber and matrix.

In preliminary studies (refs. 9 to 11), the authors showed that the tensile strength of composites of copper reinforced with tungsten fibers was a linear function of fiber content and could be represented by the following equation:

$$\sigma_c = \sigma_f A_f + \sigma_m^* A_m \tag{1}$$

where the mainline symbols are defined as

σ - tensile strength

A - area fraction or volume percent when unity length is considered and $A_f + A_m = A_c \equiv 1$

σ^* - stress taken from the stress-strain curve at a strain equivalent to that at which the ultimate tensile strength of the fiber is achieved

and the subscript symbols are defined as

c - composite

f - fiber

m - matrix

These previous studies discussed only stage III behavior, and the use of Eq. (1) was limited to the prediction of ultimate tensile strength of composites and made no attempt to predict the behavior of composites at any other value of strain.

Data obtained since the publication of the preliminary results confirm the results previously reported. These data, as well as additional work on the behavior of composites undergoing stages I, II, and IV of deformation, are presented in this paper.

General Equation for Predicting Stresses in Fiber-Reinforced Composites

Analysis of these other stages of behavior shows that Eq. (1) may be modified slightly to a more general form to allow the prediction of the stress on a composite at any value of strain:

$$\sigma_c^* = \sigma_f^* A_f + \sigma_m^* A_m \tag{2}$$

The σ^*'s used in this equation represent stresses at any particular value of strain taken from the stress-strain curves of the components in the condition in which they exist in the composite. The four stages of tensile behavior in fiber-reinforced composites will now be discussed, as well as forms of the general equation pertaining to those stages.

Stage I - Elastic Deformation of Fiber;

Elastic Deformation of Matrix

Upon loading a composite in a tensile test, the initial strain observed is elastic for the fiber, the matrix, and the composite. A mathematical expression for this behavior may be obtained by using Eq. (2) with the modification that the stresses taken from the stress-strain curves, when divided by equal elastic strains, represent the initial modulus of elasticity, and may be expressed by the following equation:

$$E_c = E_f A_f + E_m A_m \qquad (3)$$

where E is the initial modulus of elasticity. In order to determine the behavior in this narrow region of strain, low strains were required and dynamic modulus testing techniques were used. Fig. 7 shows a plot of dynamic modulus of elasticity as a function of fiber content for composites reinforced with continuous or discontinuous fibers and shows that a straight-line relation exists. The line shown was obtained by using the moduli of the two components as end points, as predicted by Eq. (3).

Stage II - Elastic Deformation of Fiber;

Plastic Deformation of Matrix

As the strain is increased, the composite passes into the second stage of deformation. To analyze this stage of deformation, it is necessary to examine the actual stress-strain curves at strains larger than those representing only the elastic behavior of the least elastic component.

This analysis is necessary because the two materials comprising the composite do not deviate from elastic behavior at the same strain.

Fig. 4 shows that the copper deviates from proportionality at about 0.03 percent strain. Below this strain, both components are acting elastically; beyond this strain, the copper is acting plastically. This figure also shows a change in slope for all of the other stress-strain curves representing the composite test specimens. Below this change in slope, the composites are undergoing elastic behavior, as described by stage I deformation. Above these strains, the slope of the copper curve is almost flat. This gives rise to a secondary "elastic" behavior of the composite, since the small portion of the load carried by the plastic copper is masked by the behavior of the tungsten. The slope of this secondary elastic portion of the curve of the composite is lower than the slope of the elastic portion, since the slope of the stress-strain curve for the copper in the composite has been reduced from 17.7×10^6 psi in the elastic portion of the curve to about 0.2×10^6 psi in the plastic portion.

Fig. 5 shows a plot of the secondary moduli of composites as a function of fiber content. The line shown is a least squares fit of the data. This curve shows that a linear relation exists between the secondary modulus and the fiber content. The behavior could be expressed by the following equation:

$$E_c' = E_f A_f + \left(\frac{\sigma_m^*}{\epsilon}\right) A_m \qquad (4)$$

where

E_c' - secondary modulus of elasticity of composite

$\frac{\sigma_m'}{\epsilon}$ - slope of stress-strain curve of matrix at a given strain

To determine whether deformation in this stage of deformation was elastic or plastic, several specimens were tested by loading to a strain where the copper matrix should have behaved plastically, while the tungsten remained elastic. A typical stress-strain curve obtained under these conditions (Fig. 8) showed an initial linear slope, as predicted by Eq. (3), a change in slope, and a second linear slope corresponding to the secondary elastic modulus.

As loading was stopped, the curve exhibited a reduction in stress with no accompanying change in strain. This is a function of the servomechanism circuit of the tensile testing machine, and this behavior has been noted in tests of pure copper and steel rod, as well as composites, and does not reflect the behavior of the test specimen.

The specimen was then unloaded. The initial slope of the unloading curve appeared to be parallel to the initial elastic slope observed during loading. Thus, the first contraction was elastic in character. A change in slope was also noted on unloading. For the remainder of the curve to zero load, the slope was almost parallel to the secondary elastic portion of the loading curve. A small amount of permanent set appeared to be retained in the specimen after the loading-unloading cycle. If the load relaxation of the servomechanism is compensated for, the permanent set would be reduced but would still be present.

In conventional materials, when the load is released, all the contraction is elastic, regardless of whether the material had been deformed plastically or elastically. For copper-tungsten composites, the initial contraction is elastic, but after a small increment of elastic contraction, the remaining contraction is what might be called secondary elastic behavior, and a change in slope is noted in the curve. This second portion of the curve indicates that, as on loading, the tungsten fibers are acting elastically while the copper is plastic. The elastic force on the fibers exerts a plastic compressive force on the copper matrix and contracts the copper, but these elastic forces are not strong enough to cause the composite to recover completely. Eventually the compressive forces in the copper balance the elastic tensile forces in the fibers. Because the composite cannot return to zero strain, the composite shows a small amount of set during cyclic loading.

Stage III - Plastic Deformation of Fiber;

Plastic Deformation of Matrix

With increasing strain, both components of the composite pass into plastic flow. The stress-strain curves presented in Fig. 3 show that the ultimate tensile strengths of the composites or the fibers themselves were achieved at about 1.2 to 1.5 percent strain. These stress-strain curves also show that the stress on the copper specimens in this strain range was about 8000 psi and did not increase significantly over the range of strain plotted in these figures. This value was used for σ_m^* in Eq. (1). The data on the strength-composition curves shown in Fig. (1) show good agreement with this equation.

Since the ultimate tensile strength of the copper, with no fibers present, is 27,800 psi, then at some very low fiber content, where the matrix is the major load-carrying component, any fibers present would not contribute substantially to the strength of the matrix and after the fibers had broken, the matrix would continue to strain and finally reach its ultimate tensile strength as if no fibers were present. Although no data has been obtained for composites containing such very low fiber contents, calculations were presented in references 9 to 11 to allow the prediction of the tensile strength of composites in this region and also to predict the fiber content below which effective reinforcement would not take place.

In addition to tensile strength, yield strength was also determined by using the 0.2 percent offset method. Fig. 6 shows a plot of such data obtained for composites, copper, and tungsten. The data were obtained from stress-strain curves. It is evident that a linear relation exists here also. Thus, the discussion previously made for the ultimate tensile strength should also pertain to the yield strength of composites. The determination of yield strength in tungsten-fiber-reinforced copper composites is complicated by the fact that there are two linear portions of the stress-strain curve. Since a line, offset 0.2 percent and parallel to the slope of the linear portion of the curve, is used in the determination of yield strength, two yield strengths (initial and secondary) are obtained depending upon which slope is used. The difference between the two values obtained will increase with decreasing fiber content. Because of the small increment of strain over which stage I behavior occurs, the yield strength obtained through conventional means may be missed entirely unless very sensitive instrumentation is used. Therefore, for composites, it may be more practical to use the slope of the stage II behavior, since it covers a much wider range of strain and is more easily measured. This may be termed a secondary yield strength.

Stage IV - Failure of Fiber-Reinforced Metallic Composites

The final stage of deformation of the composite occurs after the composite has reached its ultimate strength. Stress-strain curves shown in Fig. 3 show that the stresses on the composites and the fibers reach a maximum and then gradually drop off to failure. Fig. 2 shows a plot of percent elongation at failure as a function of fiber content. While the fibers alone exhibited from 1.3 to 2.9 percent elongation at failure, the composite show a much greater elongation.

It is postulated that the greater elongation at failure exhibited by the composites over that exhibited by the individual fibers is due to a progressive failure mechanism. As the specimen is strained, the weakest fiber eventually breaks. After this, other fibers break at their weakest points, at random locations. Eventually an accumulation of random failures in a given cross section occurs and results in failure of the remainder of the fibers. The load on the specimen is then impressed entirely upon the matrix. The amount that the matrix continues to strain after fracture of the reinforcing fibers depends upon the amount of matrix material remaining. If sufficient matrix were present, elongation continues as if no fibers were present, since only the matrix is straining. If the matrix content were low, then only a small additional amount of strain will occur before the specimen fails. Metallographic evidence seems to verify these concepts. Fig. 9 shows the fracture edge of a composite. Necking of both the individual fibers and the composite has occurred at the fracture edge, while some fibers have broken at random points along their length away from the fracture edge. Higher magnification examinations of the random location breaks also showed necking of the fibers at these breaks.

CONCLUSIONS

The results of this investigation of the stress-strain behavior of tungsten-fiber-reinforced copper composites leads to the following conclusions:

1. Stress-strain behavior of composites of this type show that all stages of deformation may be represented by the following general equation:

$$\sigma_c^* = \sigma_f^* A_f + \sigma_m^* A_m$$

2. Four stages of deformation were observed.

(a) Upon initial loading, the deformation of the matrix and fiber is elastic; the composite deforms elastically. Behavior in the initial elastic region may be defined by the equation:

$$E_c = E_f A_f + E_m A_m$$

(b) With increasing stress, the matrix deforms plastically, while the fiber remains elastic; the composite exhibits secondary "elastic" behavior. Behavior in this region may be defined by the equation:

$$E_c' = E_f A_f + \left(\frac{\sigma_m^*}{\epsilon}\right) A_m$$

(c) With increasing stress, the deformation of the matrix and the fiber becomes plastic; the composite deforms plastically. Behavior in the plastic region may be expressed by the general equation.

(d) The fourth stage represents deformation, subsequent to the attainment of the ultimate tensile strength, in which the fibers fail at random points of weakness and an accumulation of random failures results in failure of the composite.

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3. The ultimate tensile strength of the composites is proportional to the fiber content and the properties of the components as shown by the equation:

$$\sigma_c = \sigma_f A_f + \sigma_m^* A_m$$

4. Elongation of the composite, at failure, decreased with increasing fiber content. The composites showed greater elongation than the fibers which had been tested individually.

5. Composites reinforced with discontinuous fibers were fully as efficient as those reinforced with continuous fibers and were found to utilize the full strength of the fibers. The discontinuous-fiber-reinforced composites displayed the same behavior as the continuous-fiber-reinforced composites and obeyed the same equations.

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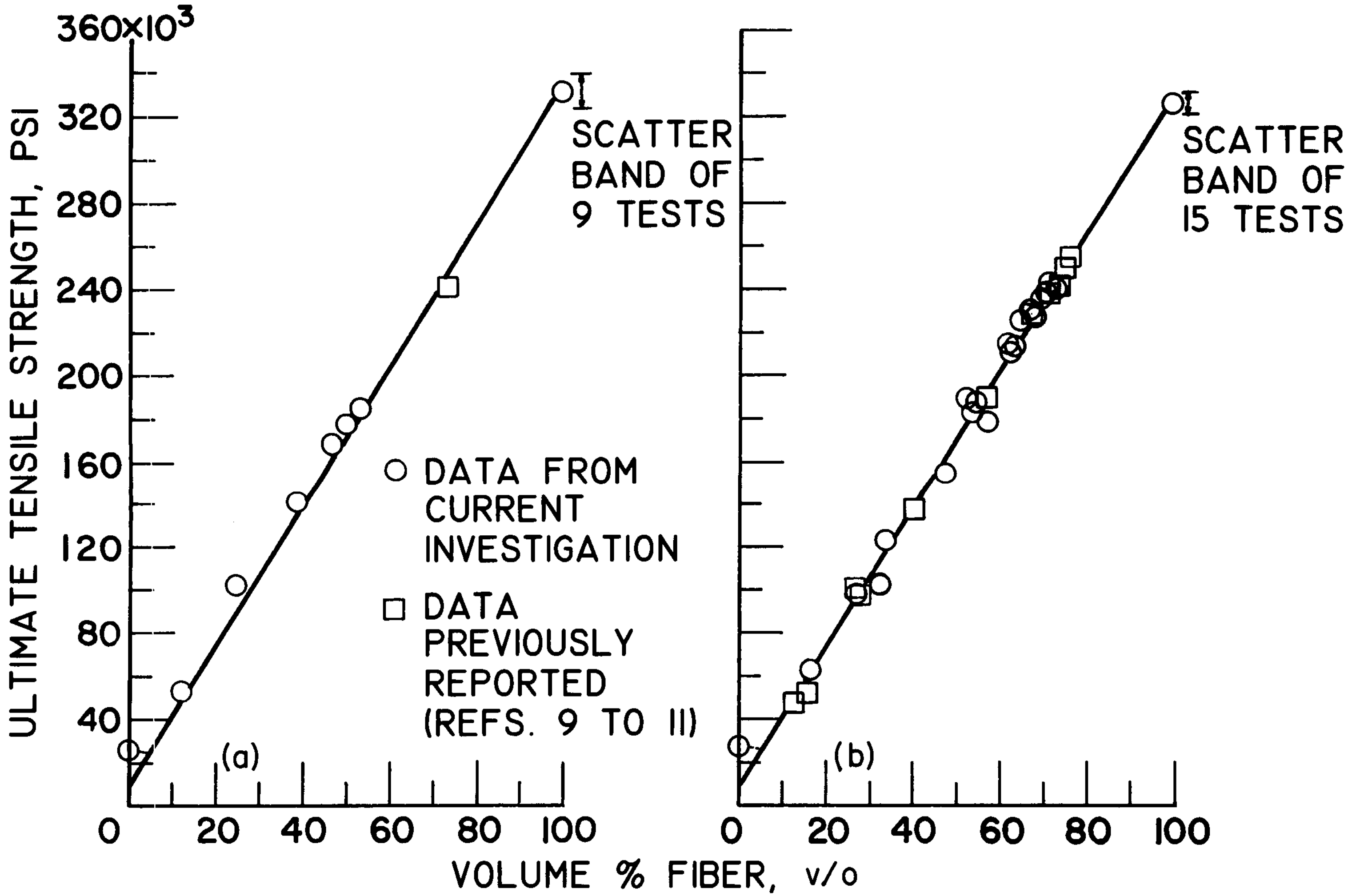
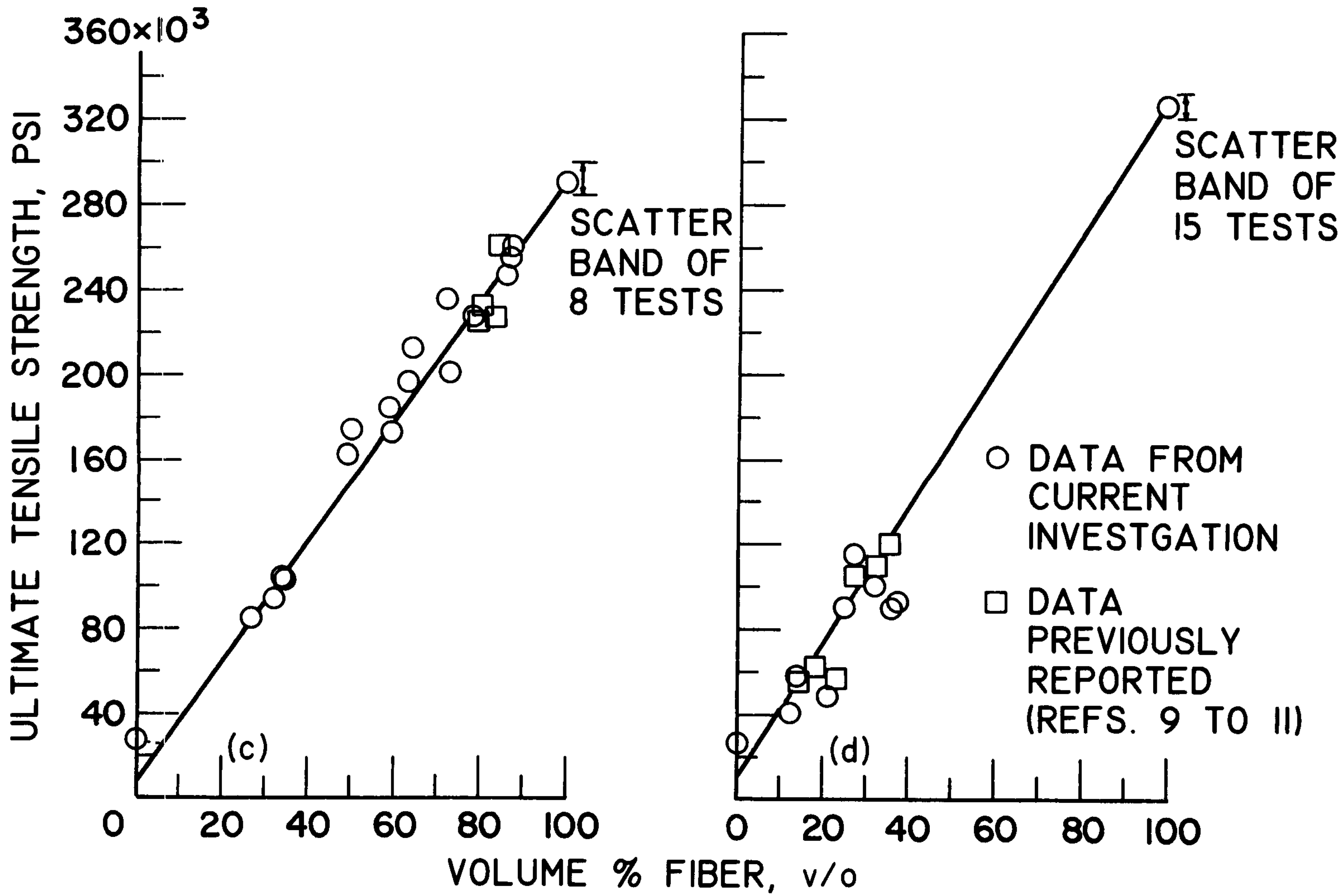


(a) Continuous reinforcement with 3-mil-diameter tungsten fibers.

(b) Continuous reinforcement with 5-mil-diameter tungsten fibers.

Fig. 1. - Tensile strengths of tungsten-fiber-reinforced copper composites.



(c) Continuous reinforcement with 7-mil-diameter tungsten fibers.

(d) Discontinuous reinforcement with 5-mil-diameter tungsten fibers.

Fig. 1. - Concluded. Tensile strengths of tungsten-fiber-reinforced copper composites.

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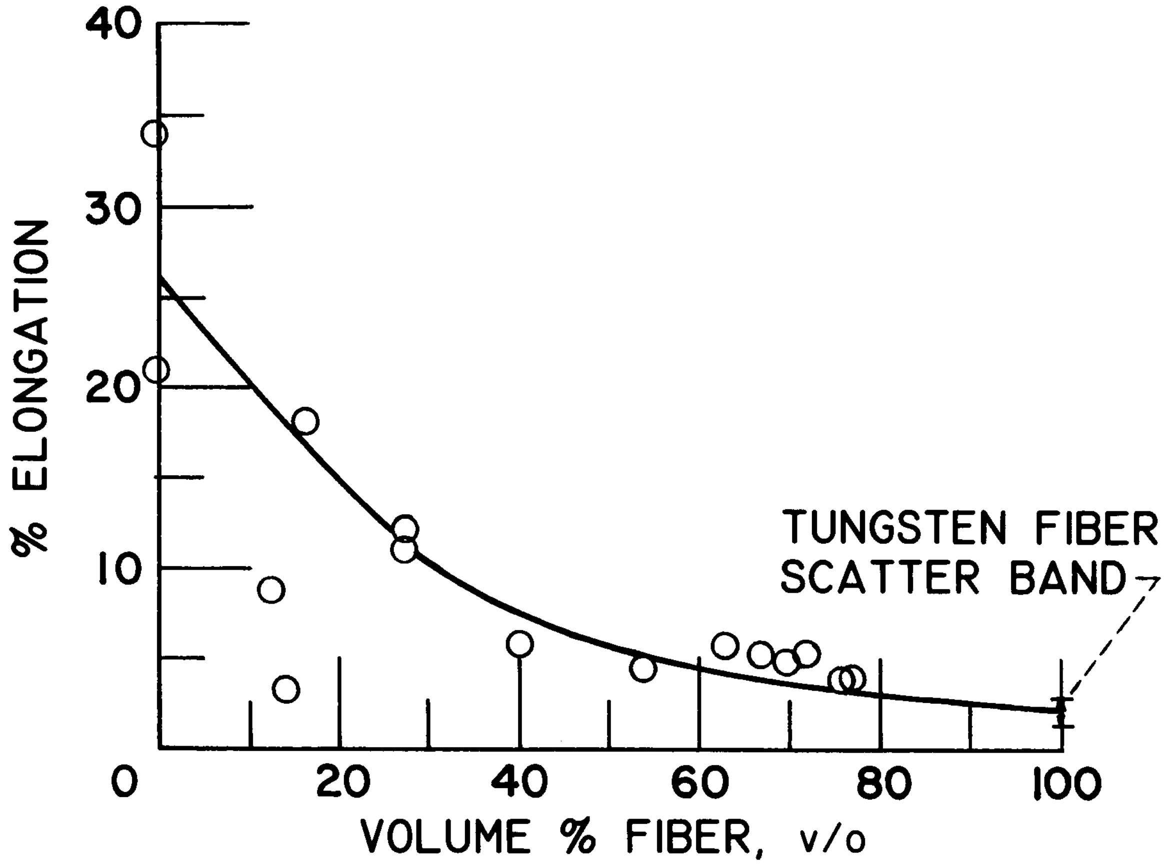
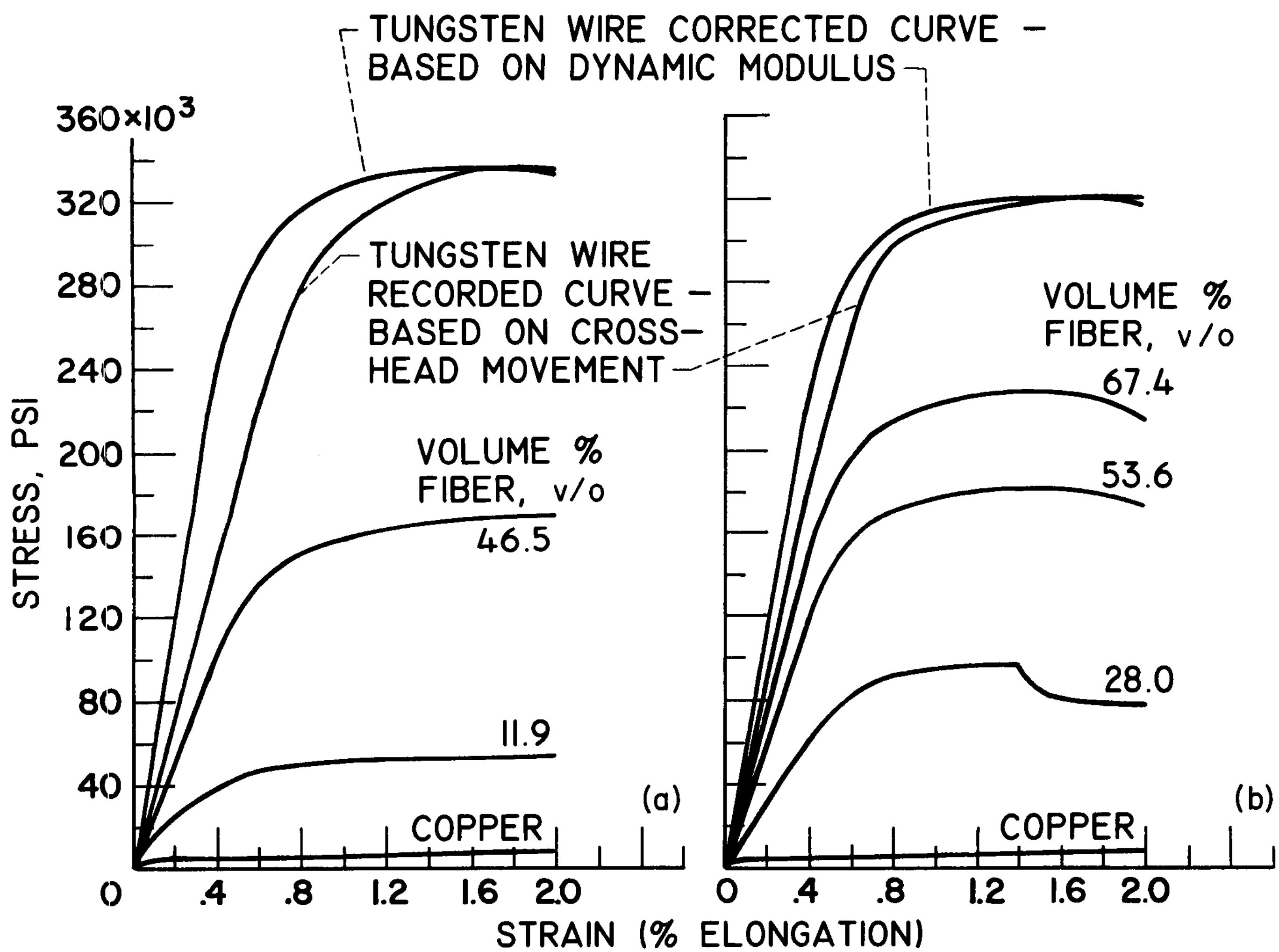


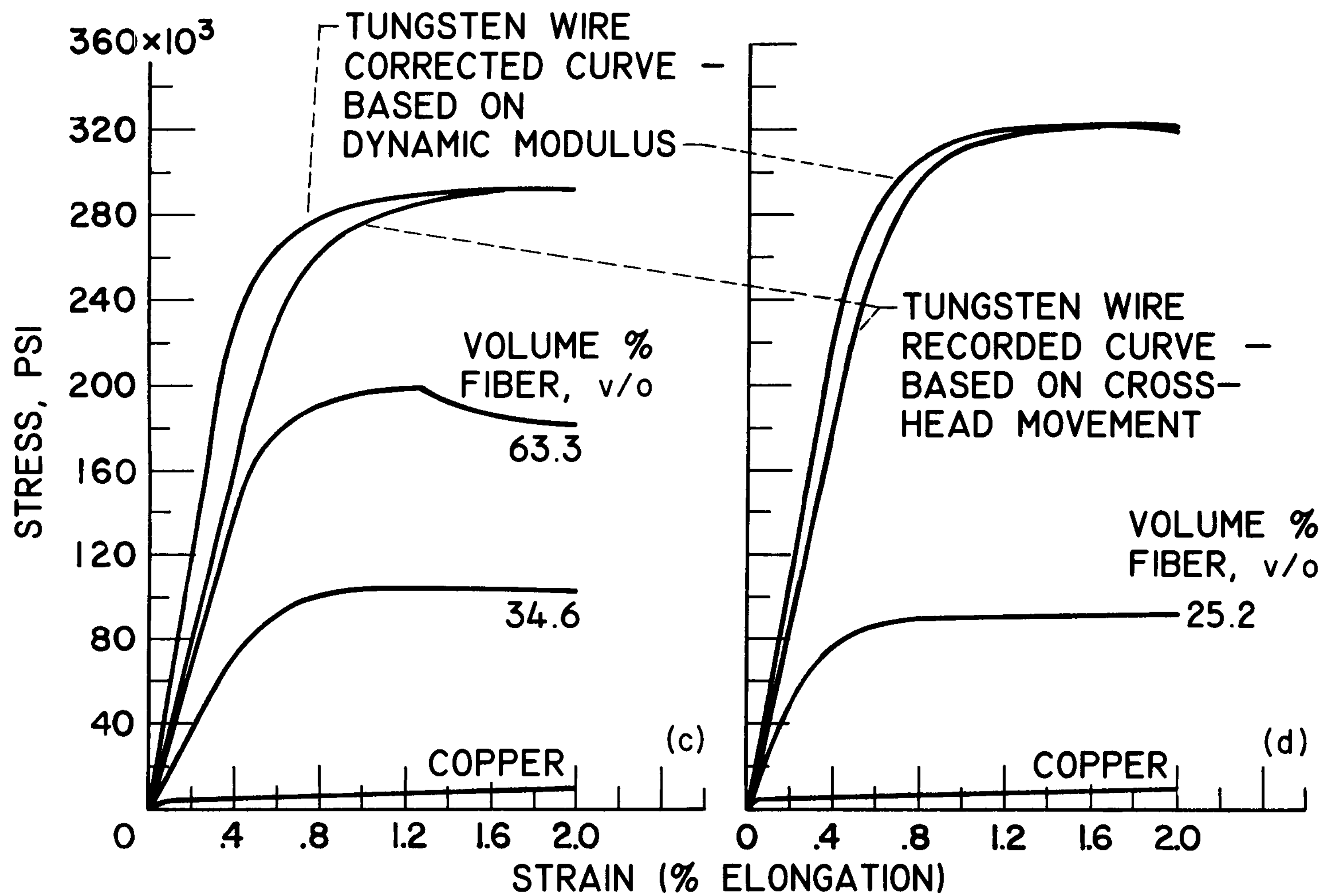
Fig. 2. - Elongation at failure of composites reinforced with continuous 5-mil-diameter tungsten fibers.



(a) 3-Mil-diameter continuous tungsten reinforcement.

(b) 5-Mil-diameter continuous tungsten reinforcement.

Fig. 3. - Stress-strain curves for tungsten wire, copper and composites reinforced with tungsten wire.



(c) 7-Mil-diameter continuous tungsten reinforcement.

(d) 5-Mil-diameter discontinuous tungsten reinforcement.

Fig. 3. - Concluded. Stress-strain curves for tungsten wire, copper, and composites reinforced with tungsten wire.

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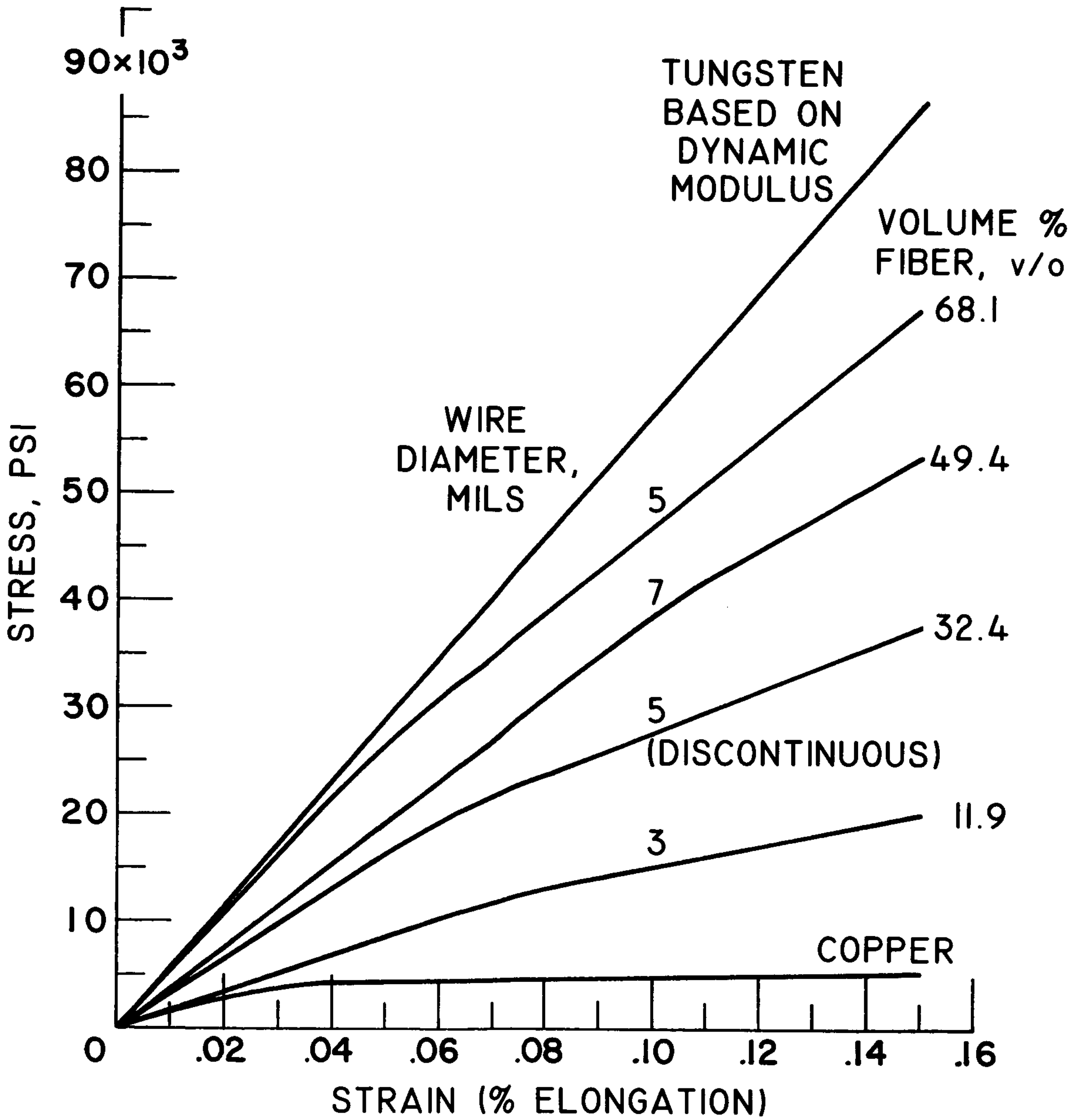

Fig. 4. - Enlargement of low-strain region of stress-strain curves of tungsten, copper, and composites reinforced with tungsten fibers.

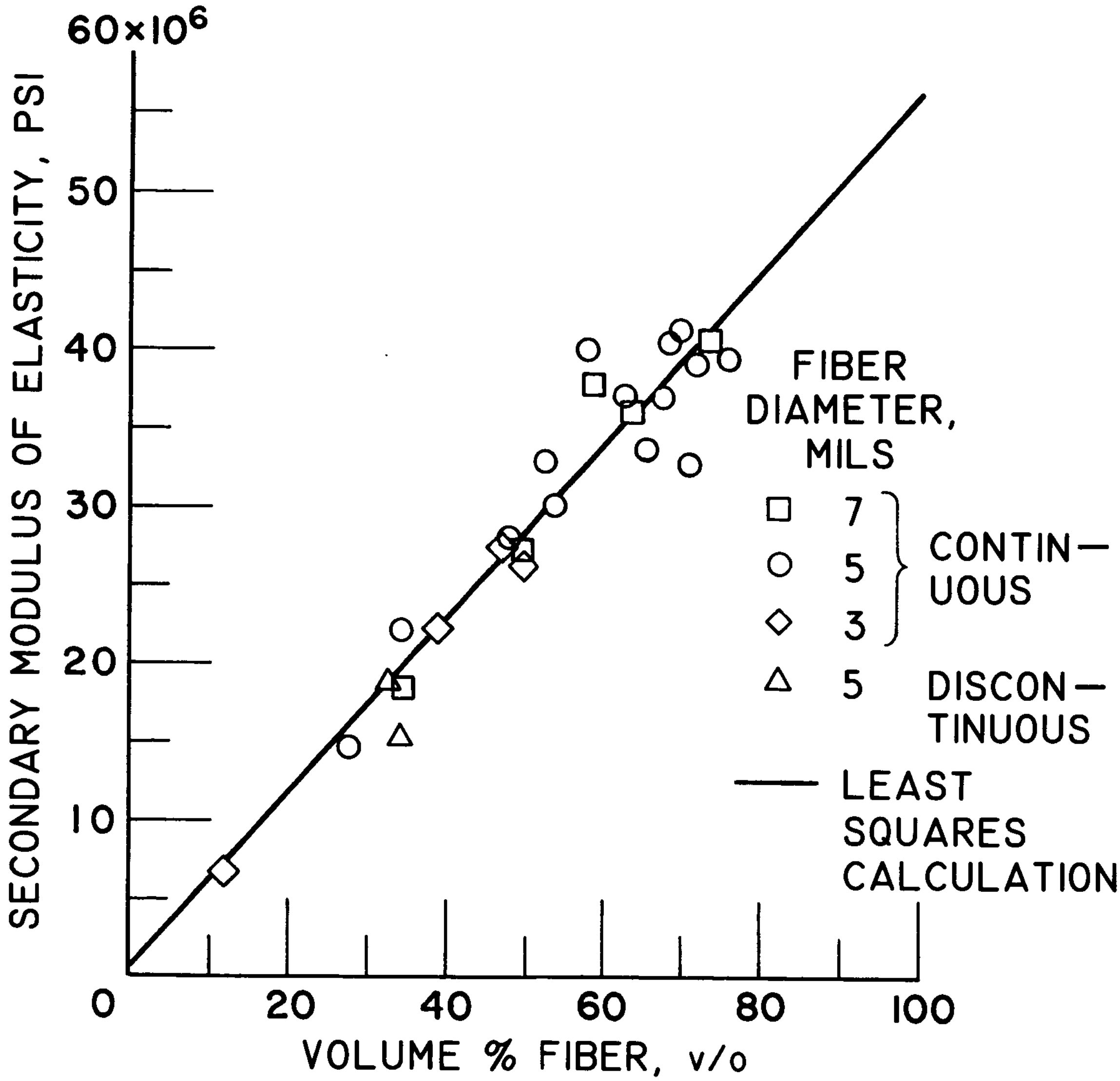

Fig. 5. - Secondary modulus of elasticity for composites reinforced with tungsten fibers.

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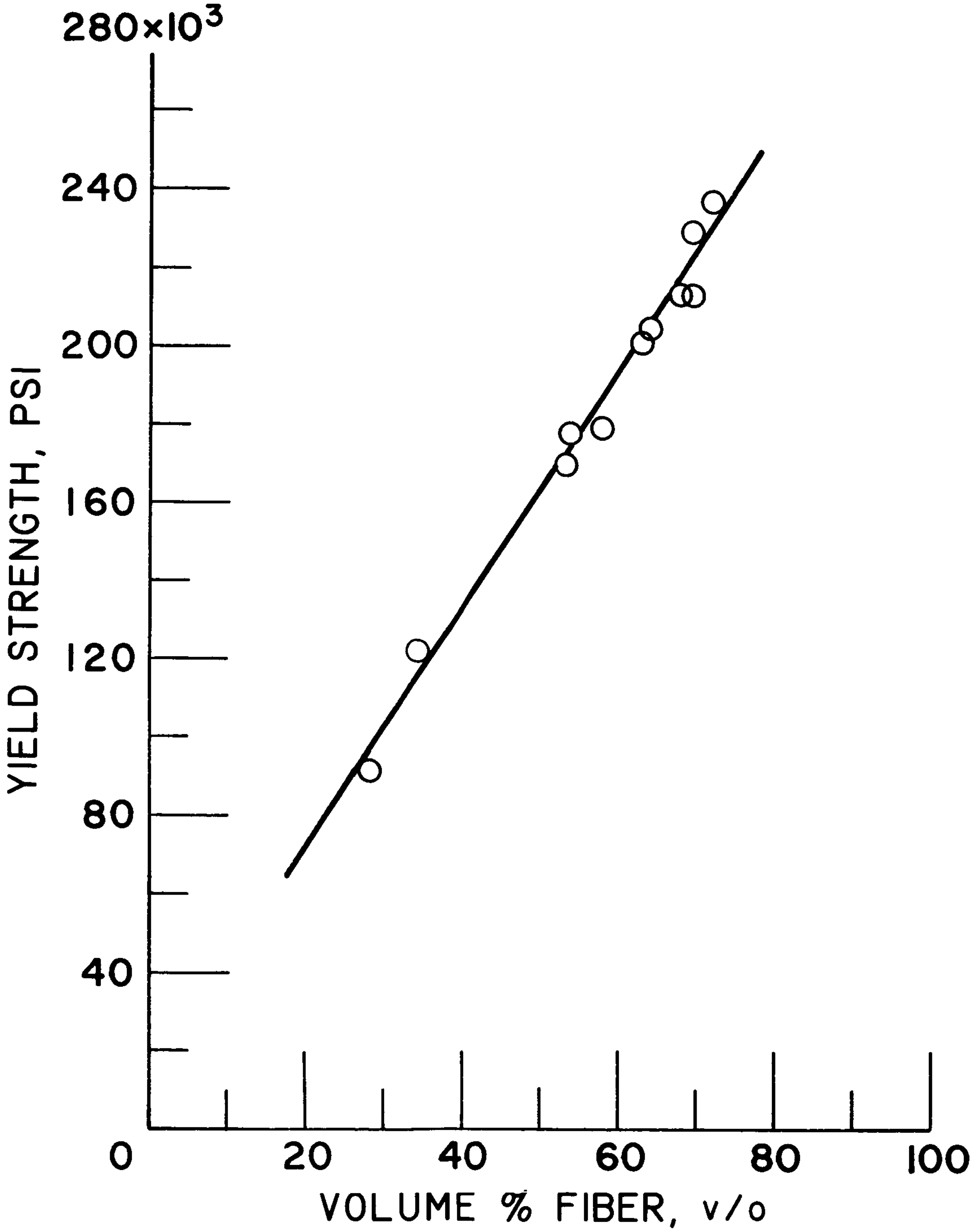

Fig. 6. - Yield strength (based on secondary modulus) of composites reinforced with continuous 5-mil-diameter tungsten fibers.

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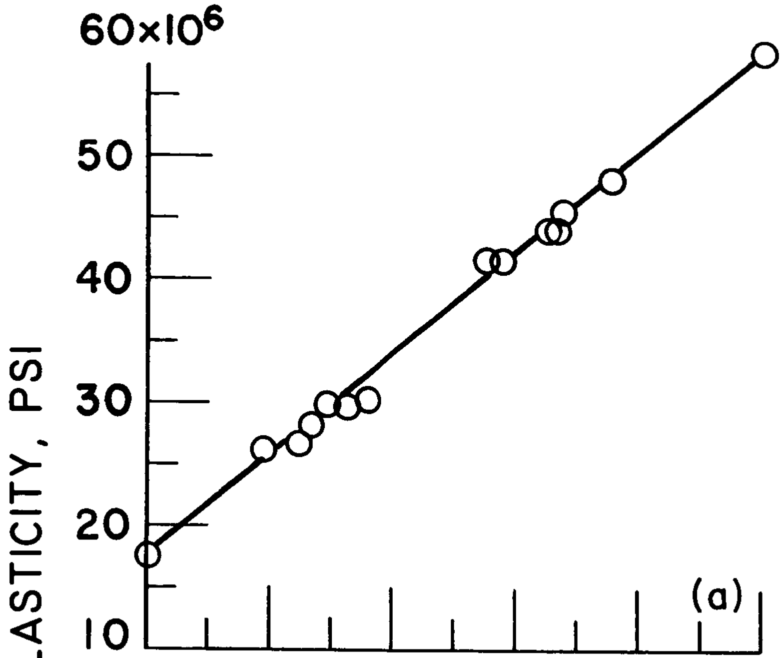
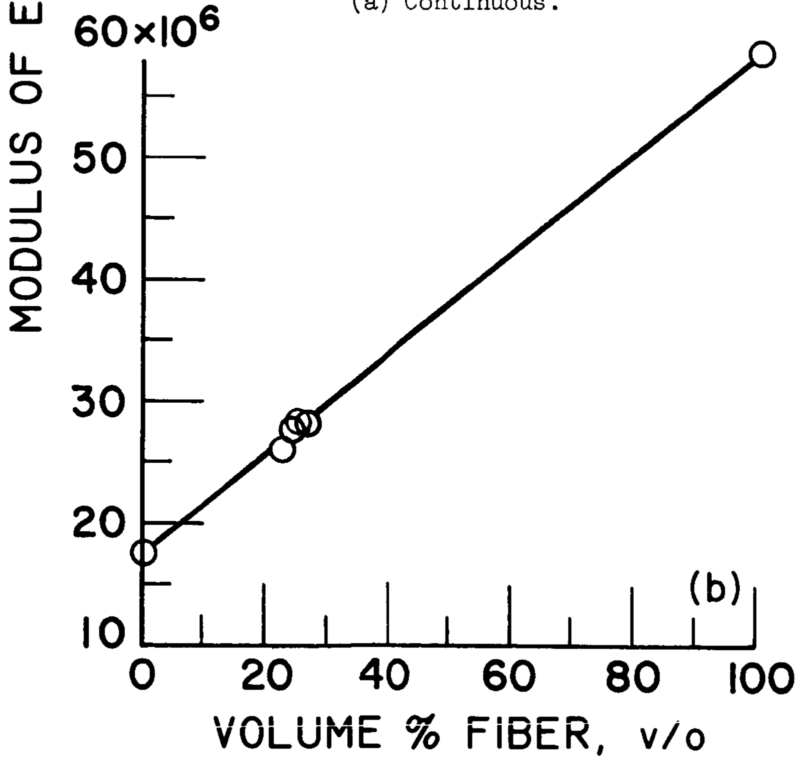


(a) Continuous.



(b) Discontinuous.

Fig. 7. - Dynamic modulus of elasticity of tungsten, copper, and composites reinforced with continuous and discontinuous 5-mil-diameter tungsten fibers.

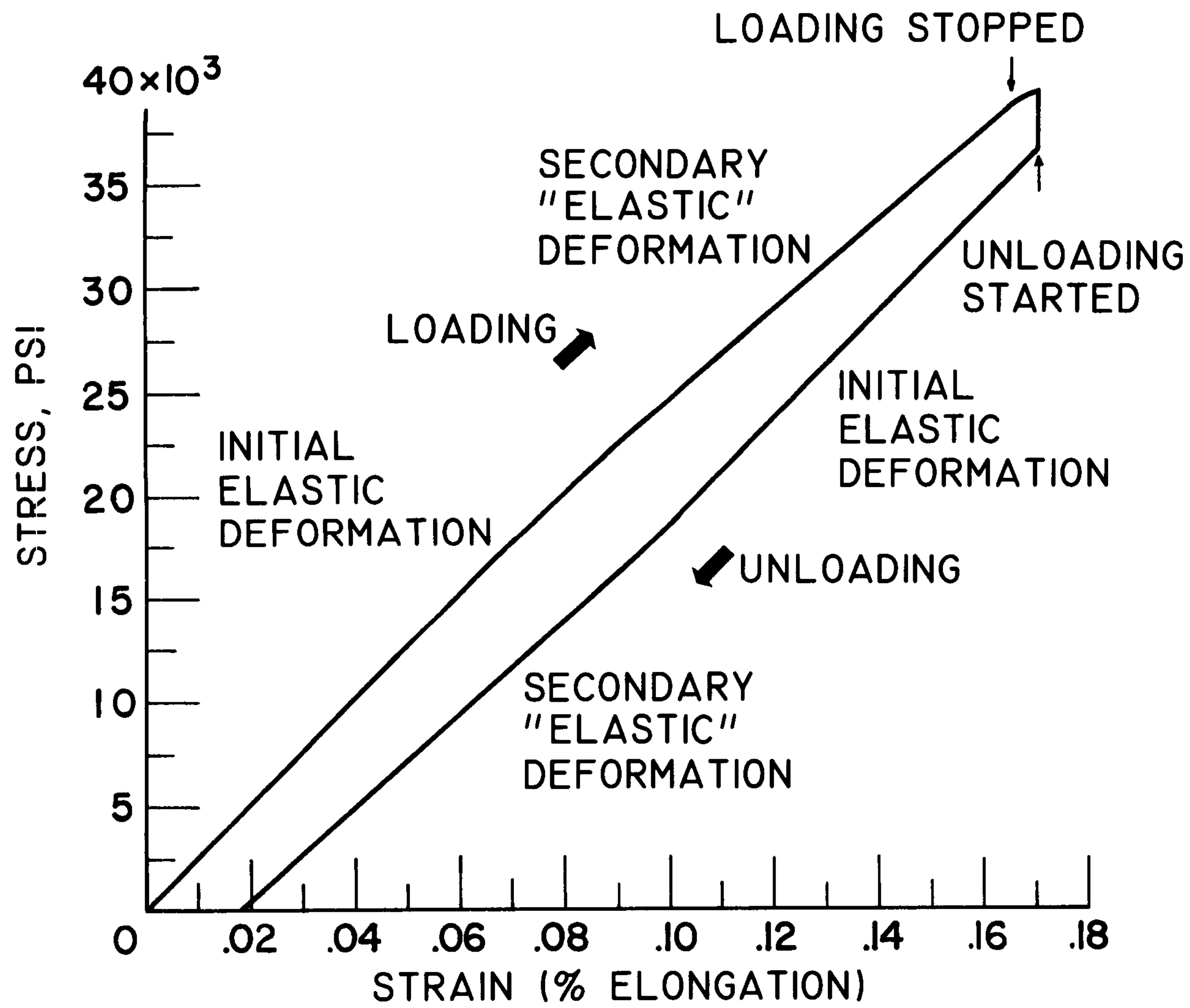


Fig. 8. - Stress-strain curve for 5-mil-diameter tungsten-fiber-reinforced copper composite upon loading and unloading. Volume percent fiber, 18.7.

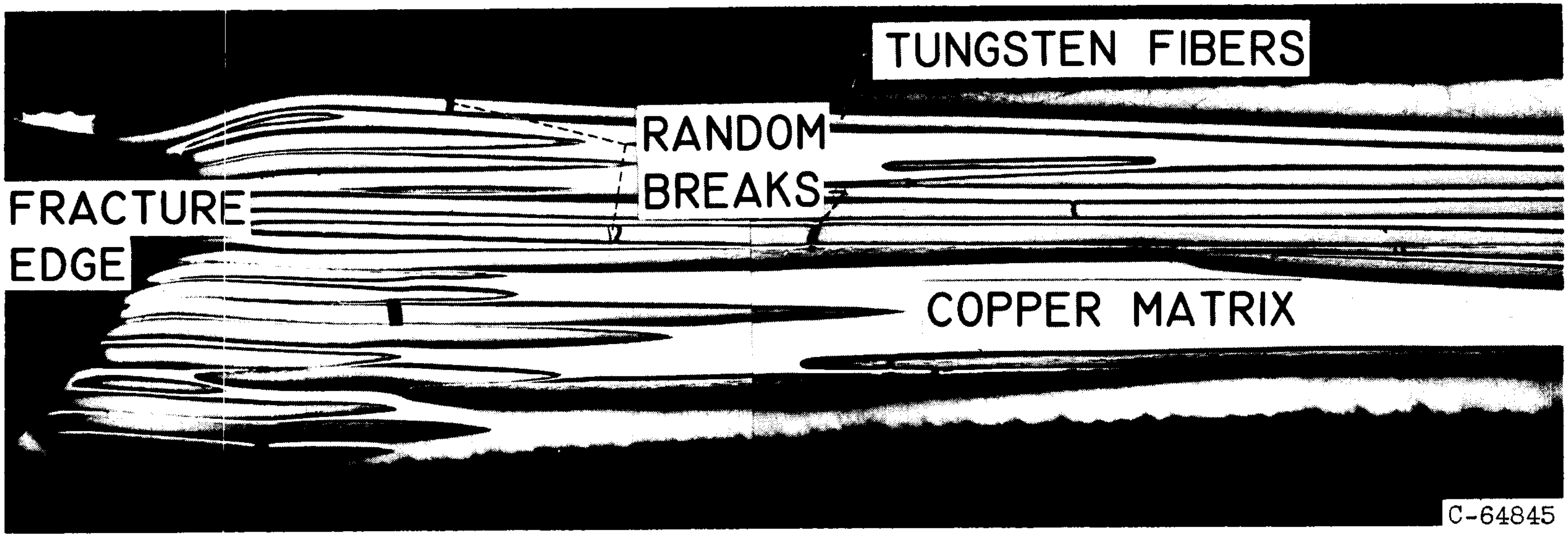


Fig. 9. - Photomicrograph of the fracture edge of a composite reinforced with continuous 3-mil-diameter tungsten fibers. Unetched; ×50.

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